Special Section: Soil–Plant–Atmosphere Continuum

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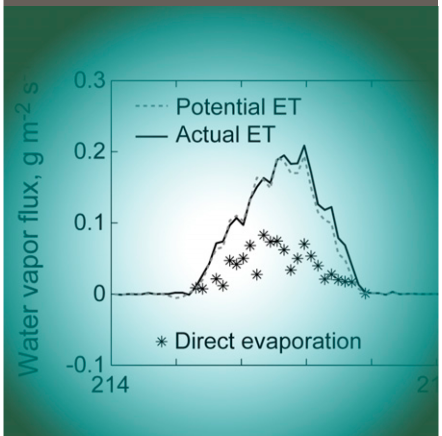

By partitioning measurements of evapotranspiration into two distinct components (direct evaporation and transpiration) using a recently developed analytical technique, near-surface hydrological processes are better characterized, including the suppression to root uptake and transpiration in the immediate aftermath of rainfall events.

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Partitioning Evapotranspiration Using an Eddy Covariance-Based Technique: Improved Assessment of Soil Moisture and Land–Atmosphere Exchange Dynamics

The capability to partition evapotranspiration (ET) measurements into two components, namely direct evaporation (*E*) from soil, leaf, and litter surfaces and transpiration (*T*) via plants is critical toward better defining hydrological processes along the soil-plant-atmosphere continuum. Such information has practical applications ranging from water resource management to climate modeling. A recently developed partitioning technique was employed using high frequency measurements of water vapor and carbon dioxide collected by an eddy covariance flux system, which was deployed over a corn (*Zea mays L.*) field near Beltsville, MD for a full growing season. The partitioning technique is based on flux-variance similarity theory and has the benefit of relying on routinely collected eddy covariance measurements, with no additional instrumentation required. Results showed an increase in the *T*/ET ratio from ∼5% during the early portion of the growing season to ∼70–80% by the time the corn crop reached maturity. This was consistent with observed dynamics of the soil moisture profile, which indicated that water was removed from deeper soil layers as the growing season progressed. The partitioned estimates of *T* are shown to be useful for the appropriate calculation of canopy conductance, a key variable in land surface models. Finally, the transient impact of rainfall events were examined, in which the suppression of *T* and enhancement of *E* were observed for up to several days following rainfall. Insight gained through the partitioning of ET fluxes has the potential to significantly improve the structure and parameterization of land surface hydrological models.

Abbreviations: LAI, leaf area index; WUE, water use efficiency.

Micrometeorological techniques such as eddy covariance and energy balance Bowen ratio measure total evapotranspiration (ET), the sum of direct evaporation (*E*) and transpiration (*T*) fluxes. Direct evaporation consists of bare soil evaporation along with evaporation from leaf and litter interception stores, while transpiration refers to the uptake of soil moisture through plant roots and its subsequent release to the atmosphere through stomata, the pores on leaf surfaces. These fundamentally different evaporative processes have distinct forcings and constraints, with *E* regulated by factors such as the rate of delivery of moisture to the soil surface (Black et al., 1969; Parlange et al., 1992) or the amount of water in interception stores, whereas *T* is influenced by vegetation physiological factors that govern the degree of stomatal closure. The respective processes also have disparate influences on the evolution of the soil moisture profile, as *E* results in the depletion of water stored above or within the uppermost soil layer, while *T* can lead to reduction in soil moisture at greater depth, as shaped by the vertical distribution of roots and their uptake efficiency. The separation of ET into discrete components is needed to better characterize both surface and subsurface hydrological processes and to address practical issues such as discerning the effects of rainfall and irrigation on crop water use. In this paper, a recently developed ET partitioning technique is applied to flux measurements collected over an agricultural field (corn crop), and the results are used to highlight the unique information that can be gained related to understanding soil-plant-atmosphere processes if such partitioned fluxes are available.

A number of approaches have been developed to partition ET fluxes, including those that have combined eddy covariance with other instrumentation such as sap flux sensors (e.g., Kurpius et al., 2003; Unsworth et al., 2004; Rana et al., 2005; Tang et al., 2006), microlysimeters (e.g., Singer et al., 2010; Agam et al., 2012), and flux chambers (e.g., Stannard and Weltz, 2006; Daikoku et al., 2008; Raz-Yaseef et al., 2010). Although such approaches have led to advances in estimating the relative partitioning of ET fluxes, a complicating issue is the mismatch in footprints between the landscape-scale fluxes derived by eddy covariance and the more localized fluxes obtained by the other instruments. A technique that avoids this issue involves high-frequency measurements of isotopes in water vapor, which can be used within the eddy covariance framework for the purpose of flux partitioning (Lee et al., 2005; Welp et al., 2008). The number of studies reporting the successful implementation of this methodology is limited, however, due to factors such as substantial instrumentation costs and difficulties associated with quantifying the isotopic fractionation in the water vapor from soil and leaf sources (e.g., Griffis et al., 2011).

A recently developed ET partitioning technique is applied in the present study, one that relies on standard eddy covariance flux measurements and also considers fluxes of carbon dioxide, a scalar whose exchange between the land surface and atmosphere is inherently linked with water vapor. The technique is based on the assumption that flux variance similarity between water vapor and carbon dioxide separately applies to stomatal fluxes (transpiration and photosynthesis) and non-stomatal fluxes (direct evaporation and respiration) (Scanlon and Sahu, 2008; Scanlon and Kustas, 2010). A major benefit of this technique is that no additional instrumentation is needed beyond what is involved in a typical eddy covariance setup, as most infrared gas analyzers used to measure water vapor concentrations also measure carbon dioxide concentrations. The only input needed to this approach is the vegetation water use efficiency (WUE, defined as the ratio of carbon dioxide gain per unit water loss at the leaf level), which may be estimated based on gradient considerations and some knowledge of the inter-stomatal CO_2 concentration (C_i). This technique was previously shown to provide reasonable estimates for both water vapor and carbon dioxide flux partitioning over the course of a growing season for a cornfield in Beltsville, MD. (Scanlon and Kustas, 2010).

The present analysis focuses exclusively on ET flux partitioning and how the land surface hydrological processes can be better resolved with such information. The following issues, in particular, will be addressed: (i) how direct evaporation and transpiration fluxes differentially impact the vertical soil moisture profile, (ii) how plant canopy conductance can be better characterized when the transpiration component of ET is known, and (iii) how precipitation events have a transient impact on the ET flux components.

Eddy covariance measurements of ET fluxes are now widespread, but information regarding how ET fluxes are partitioned remains scarce. This amounts to a current scientific need, because proper structural development and parameterization of land surface hydrological models demands measurements of discrete E and T fluxes. In addressing the issues mentioned above, we confront some of the more challenging aspects involved in accurately depicting hydrological processes along the soil-plant-atmosphere continuum. Our aim is to demonstrate that insight into these processes can be obtained through the analysis of routinely collected eddy covariance data when interpreted in the context of flux-variance similarity theory.

Materials and Methods

Field Methods

Eddy covariance data were collected over a cornfield near Beltsville, Maryland from 28 June to 24 Aug. 2008 at the Optimizing Production Inputs for Economic and Environmental Enhancement (OPE^3) research site operated by the USDA Agricultural Research Service. Corn was planted 2 d before the onset of the flux measurements and reached maturity by the end of the measurement period. The flux tower was surrounded by a relatively homogeneous corn crop, with a minimum fetch of 200 m in the southeast direction. Mean corn height and leaf area index (LAI) were collected on a roughly weekly basis throughout the growing season, with the latter measured by a LAI2000 light meter on repeatable transects generally upwind of the flux tower. The soil profile at the research site is characterized by several meters of sandy loam overlying a clay lens.

Eddy covariance instrumentation consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc.) and an infrared gas analyzer (LI-7500, LI-COR Biosciences), both of which recorded measurements at a frequency of 10 Hz. These instruments were placed at a height of 4 m above the ground surface. Other relevant instrumentation at the site included a tipping bucket rain gauge (TE525, Texas Instruments) and a net radiometer (CNR-1, Kipp & Zonen, Inc.). Six soil heat flux plates (REBS HFT-1, Campbell Scientific, Inc.) were installed at depths of 0.08 m and Type-T soil thermocouples (Model 105T, Campbell Scientific, Inc.) were positioned above these at depths of 0.02 m and 0.06 m to quantify heat storage. Volumetric soil moisture was measured with capacitance probes (EnviroSCAN, Sentek) installed at five separate sites within 50 m of the flux tower. At each site, probes collected measurements at 0.10, 0.30, 0.50, and 0.80 m depths. A full description of the instrumentation at the OPE^3 research site can be found in Crow et al. (2008).

Data Analysis

The flux partitioning procedure was performed as described in Scanlon and Kustas (2010). In brief, Reynolds averaging was performed on the high-frequency wind speed and scalar data using half-hour averaging times, and adjustments were made to the measured water vapor and carbon dioxide concentrations to account for density fluctuations (Detto and Katul, 2007). Wavelet filtering was performed on the half-hour time series to remove low-frequency information, which can be introduced by large-scale processes associated with entrainment or non-stationarity. For each half-hour period, wavelet filtering was applied over progressively smaller scales until a solution was obtained that satisfied the requirement of flux-variance similarity for both the stomatal and non-stomatal fluxes (in some cases, the partitioning procedure fails to converge on a solution). To recover the measured ET fluxes, it was assumed that the "missing" portion of the fluxes (due to its removal by the high-pass wavelet filtering) has a T/ET ratio equivalent to that determined from the filtered fluxes.

Flux partitioning was performed over the entire measurement period, 28 June to 24 Aug. 2008 only during daytime conditions, defined as when downwelling shortwave radiation was >10 W m^{-2}. During the nighttime, the low-level ET fluxes consist of some combination of transpiration, direct evaporation, and condensation. The only input to the partitioning technique is leaf-level WUE, which can be estimated as:

$$\mathrm{WUE} = 0.7\frac{\left(\overline{c_s} - \overline{c_i}\right)}{\left(\overline{q_s} - \overline{q_i}\right)} \qquad [1]$$

(Campbell and Norman, 1998), where $\overline{c_s}$ and $\overline{c_i}$ are the half-hourly mean carbon dioxide concentrations in the vicinity of the leaf surface and within the stomatal aperture, respectively, and $\overline{q_s}$ and $\overline{q_i}$ are the half-hourly mean water vapor concentrations at these two locations. The coefficient 0.7 accounts for the differences in diffusion and convection between water vapor and carbon dioxide through the stomatal aperture. As described in Scanlon and Kustas (2010), $\overline{c_s}$ and $\overline{q_s}$ are extrapolated from measured concentrations above the canopy by considering mean vertical profiles, $\overline{q_i}$ is estimated by assuming 100% relative humidity within the stomata, as dictated by foliage temperature, and $\overline{c_i}$ is estimated using the relationship $c_i = 0.44c_s$, which is drawn from leaf-level measurements of corn (Kim et al., 2006). No additional parameterization and no calibration are required for this ET flux partitioning procedure. It should be noted that this simplified method for estimating WUE was applied in the absence of more detailed leaf-level information, which could be used to provide more accurate estimates of the c_i/c_s ratio when stomatal conductance is significantly reduced, such as during low light or drought conditions. In settings where more detailed leaf-level measurements are available, alternative expressions could be used to estimate c_i/c_s and WUE.

The partitioned ET results are integrated with independently measured environmental variables to address the stated objectives. When the partitioned half-hour fluxes are aggregated to daily timescales, gaps in the half-hour time series are filled by assuming that T/ET ratios for the missing fluxes are identical to the T/ET ratios for the available data on the particular day.

Results

Application of the partitioning procedure to the eddy covariance data yielded half-hourly fluxes of E and T (Fig. 1). Direct evaporation was found to dominate during the post-planting period, when bare soil conditions prevailed (Fig. 1a). Emergence and growth of the corn crop led to progressively lower contributions of E to the total ET flux throughout the growing season (Fig. 1b and 1c), which was compensated by higher contributions from T to the total ET. Also noticeable are periods of missing data, such as on Julian Day 183 (Fig. 1a). In such cases, the partitioning procedure either failed to converge on a solution or converged on multiple solutions. Overall, partitioned flux information was missing from 23% of the half-hour periods due to one of these factors.

Flux partitioning over the growing season appears to be primarily influenced by two factors: leaf area index and the occurrence of precipitation events (Fig. 2). As LAI ramps up throughout the growing season (Fig. 2a), T accounts for an increasingly larger portion of the ET flux (Fig. 2c). The ratio T/ET is around 5% during the post-planting period and increases to approximately 70–80%

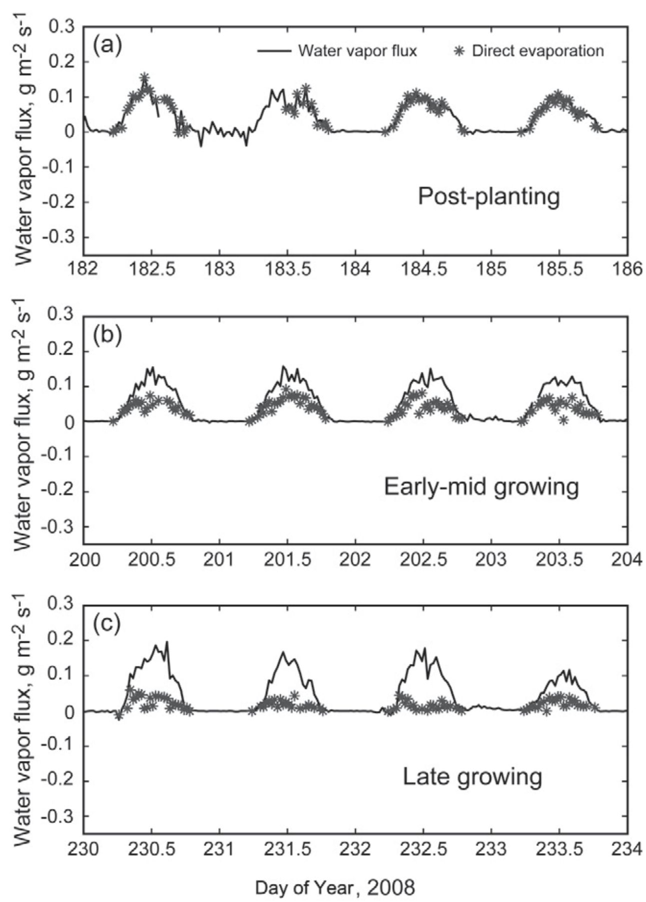

Fig. 1. Half-hourly partitioned ET fluxes for select days during the (a) post-planting, (b) early-to-mid growing, and (c) late growing seasons. Direct evaporation (E) is dominant in the early portion of the growing season but accounts for a smaller portion of the ET flux as the growing season progresses. By late growing season, transpiration (T) accounts for the largest portion of the ET flux.

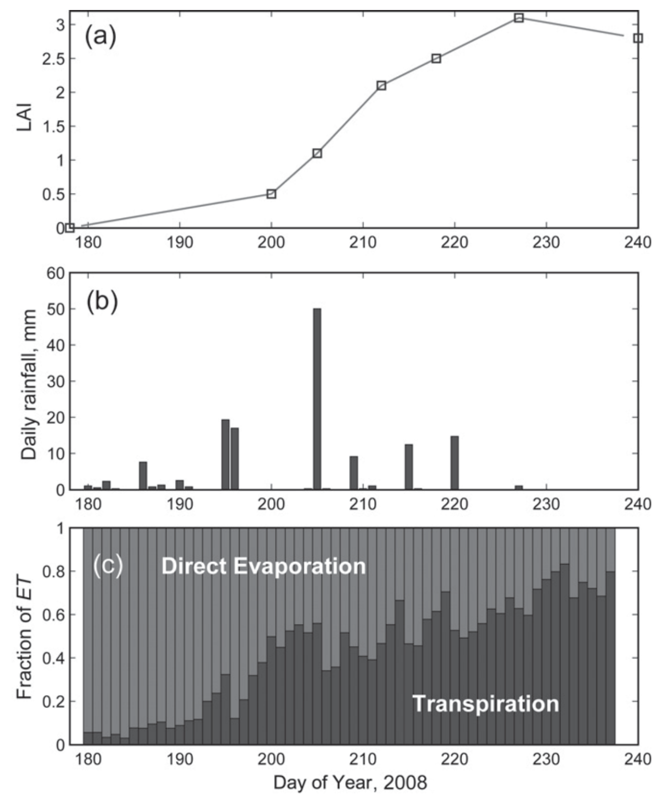

Fig. 2. Times series of (a) leaf area index, (b) daily rainfall totals, and (c) fraction of ET from direct evaporation and transpiration throughout the growing season. Partitioned fluxes yielded by the flux-variance based partitioning procedure (Scanlon and Kustas, 2010) are consistent with the long-term growth of the corn crop and appear to be influenced by rainfall events.

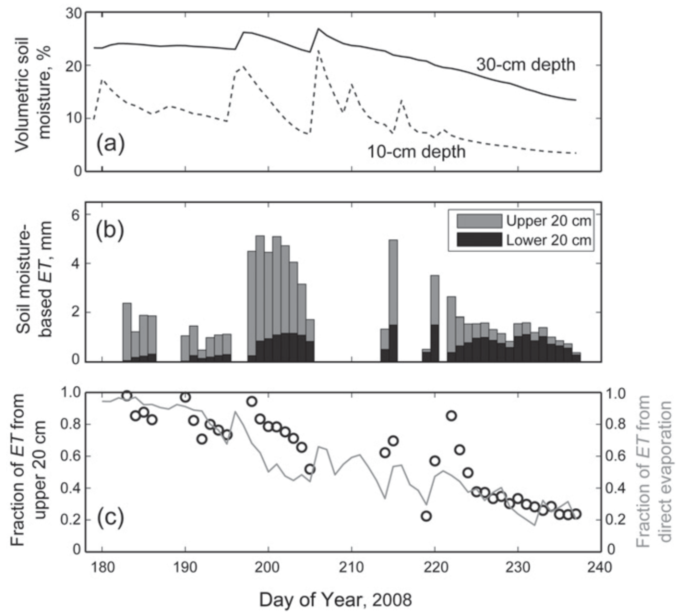

Fig. 3. Time series of (a) volumetric soil moisture measured at 10-cm depth (dashed line) and 30-cm depth (solid line), (b) inferred ET from the upper and lower depths based on temporal changes in volumetric soil moisture at these two depths, and (c) fraction of ET from the upper 20 cm based on soil moisture mass balance (circles) and fraction of ET from direction evaporation based on the flux partitioning technique (line).

by the time the corn crop reaches maturity. The partitioning results also detect a transient influence from precipitation events (Fig. 2b), in which rainfall arrival leads to the suppression of T and the enhancement of E in terms of their relative contributions to ET. This transient phenomenon is explored in further detail below.

Volumetric soil moisture (θ) time series measured by the capacitance probes installed at 10-cm and 30-cm depths are influenced by infiltration, evapotranspiration, and vertical redistribution processes (Fig. 3a). By making the rough assumption that measurements made by the probes at 10-cm depth are representative of θ over an upper soil layer (0–20 cm depth) and measurements made by the probes at 30-cm depth are representative of θ over a lower soil layer (20–40 cm depth), mass balance can be applied to convert changes in θ to estimates of ET fluxes from the respective layers. As a way to screen for situations when infiltration and vertical redistribution may have a significant impact the soil moisture-based estimates of ET, mass balance calculations were performed only when the following conditions were met: (i) θ in both layers declined over a daily time step, and (ii) the sum of ET calculated from the two layers did not exceed the rate of potential (Priestly and Taylor, 1972) evapotranspiration. These soil moisture–based estimates indicated that ET was mainly derived from the upper portion of the soil horizon during the first half of the growing season, and then was dominated by ET from the lower portion of the soil horizon throughout the remainder of the growing season as the soils dried (Fig. 3b). These results are consistent with those yielded by the partitioning procedure (Fig. 3c), which showed an early growing season dominance of E (which removes water from the upper soil layer), giving way to the later dominance of T (which removes water from both the upper and lower soil layers, and is influenced by the vertical distribution of roots).

The partitioned ET flux information is also useful for characterizing plant canopy processes. In particular, canopy conductance (g_c) describes stomatal control exerted by plants in regulating T, and is a function of both the plant canopy microclimate and LAI. This variable, which plays a key role in the calculation of ET in land surface models (e.g., Lawrence et al., 2007; Mu et al., 2007; Kume et al., 2011), is commonly derived by entering measurements into an inverted form if the Penman–Monteith (Monteith, 1973) equation:

$$g_c = \frac{\mathrm{ET_{meas}}\gamma g_a}{\dfrac{\Delta Q_n}{L_v} + \dfrac{\rho_a c_p D g_a}{L_v} - \mathrm{ET_{meas}}(\Delta + \gamma)} \qquad [2]$$

where $\mathrm{ET_{meas}}$ is the measured evapotranspiration (kg m^{-2} s^{-1}), γ is the psychrometric constant (mb K^{-1}), Δ is the slope of the saturation vapor pressure curve (mb K^{-1}), g_a is aerodynamic conductance (m s^{-1}), Q_n is available energy (W m^{-2}), ρ_a is air density (kg m^{-3}), c_p is heat capacity of the air (J kg^{-1} K^{-1}), L_v is the latent heat of vaporization (J kg^{-1}), and D is the vapor pressure deficit (mb). Estimates of g_c differ depending the input for ET_{meas} in (2), whether it is total ET, as is common when eddy covariance data are used, or T, which is more appropriate for parameterizing the canopy function (Fig. 4). Portions of ET that arise from bare soil evaporation or canopy interception contribute to consistently larger estimates of g_c relative to the estimates of g_c based on T alone.

The transient impact of the rainfall events on the flux partitioning, as first mentioned in reference to Fig. 2, is examined in greater detail in Fig. 5. Here, ET time series are shown for 2 days, in which rainfall is received during the nighttime between the first and second day. Following the rainfall E is enhanced relative to the first day, especially during the morning hours. Conditions were relatively moist for both days, resulting in ET being close to the potential rate.

To analyze the impact of precipitation on flux partitioning throughout the growing season, additional paired dry and wet days such as those shown in Fig. 5 were identified. Of particular interest were paired days in which rainfall was received during the nighttime between the 2 days. The impact of the rainfall was evaluated with respect to the differences between the partitioned E and T fluxes and what they would have been if the relative partitioning were the same as the preceding, dry day. As shown in Fig. 6, these differences tended to scale with canopy LAI, such that E was enhanced (and T was suppressed) during the post-rainfall day by as much as 1.0–1.5 mm when the canopy was partially to fully developed.

Discussion

Eddy covariance measures total ET, but more advanced analysis is required to partition these measurements into E and T. The technique developed by Scanlon and Sahu (2008) and Scanlon and Kustas (2010) was applied to data collected over a cornfield for a full growing season, and the results show that the partitioning is driven largely by LAI and the arrival of precipitation events (Fig. 2). At the time of crop maturity, T/ET was approximately 70–80%, which is consistent with the values reported by Kang et al. (2003) for an irrigated corn crop with a similar LAI of 3.0. In Kang et al. (2003), lysimeter measurements of both bare soil evaporation and total evapotranspiration were used to define T/ET. Other field-based studies have reported higher T/ET values, but these have been associated with denser corn crops. For example, Jara et al. (1998), using sap flux, microlysimeter, and energy balance Bowen ratio methods, found that T/ET was generally between 85 and 95% for a continuously irrigated corn field with LAI ≈ 4 to 5. Bethenod et al. (2000) used sap flux measurements of T combined with energy balance Bowen ratio measurements of ET and reported T/ET values of 88–90% for a non-irrigated field with LAI ≈ 4. As leaf area increases, the amount of available energy that reaches the soil surface decreases, resulting in lower bare soil evaporation and higher T/ET ratios.

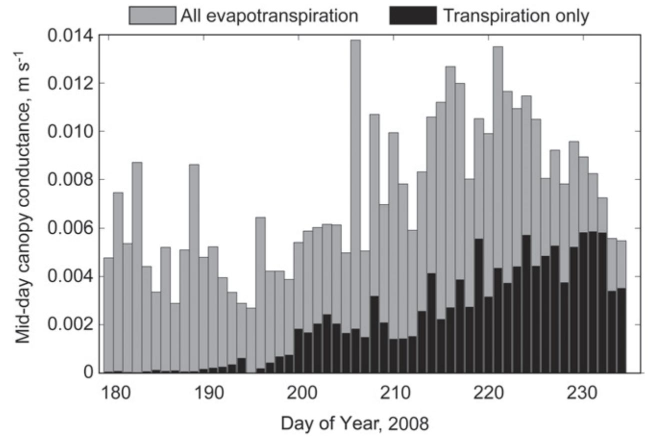

Fig. 4. Mean mid-day (defined as 8:30 a.m. to 4:00 p.m. local time) canopy conductance, calculated from an inverted form of the Penman–Monteith equation using all evapotranspiration (gray bars) and transpiration only (black bars) as inputs.

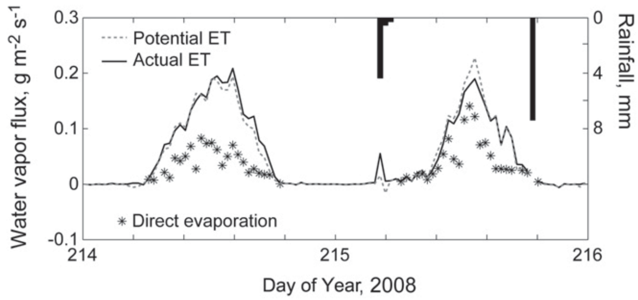

Fig. 5. Potential and actual ET, along with estimates of direct evaporation (E) for 2 d. Rainfall was received during the pre-dawn hours on Julian Day 215, enhancing E and suppressing T later that day. For both days, ET remained close to the potential rate.

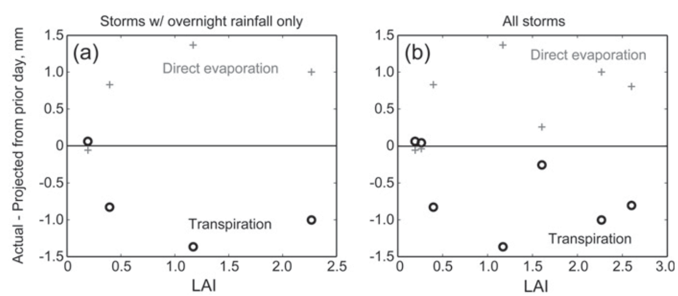

Fig. 6. Differences between the actual and projected direct evaporation (E) and transpiration (T) fluxes (a) during the day following an overnight rainfall and (b) during the day following or on the same day as a rainfall event, plotted as a function of canopy leaf area index (LAI). Projected fluxes refer to the fluxes that would have occurred if the relative partitioning between E and T were the same as the previous, non-rainfall impacted day.

The distinct ET flux components have disparate impacts on the soil moisture profile. Evidence of this can be found in the time series of volumetric moisture at two depths (Fig. 3a), in which declines in θ through time for the shallow (10 cm) probe are steeper than for the deeper (30 cm) probe during the first half of the growing season, but the relative steepness of these declines reverses by the second half of the growing season. When converted to ET fluxes (Fig. 3b), this reveals a growing dominance of "deeper" water that contributes to ET through the growing season. This is consistent with increased contributions of T to ET during this timeframe (Fig. 3c), in which water is removed at depth by the root system of the corn crop. Consistent discrepancies between these two measures can be found during Julian Days 198–206, which may be attributed to the fact that T likely removes water mostly from the shallow soil layer during the early to middle stages of corn growth, as the root system is becoming established and has yet to descend to the deeper soil layers.

As pointed out above, the portion of ET that is relevant to the calculation of canopy conductance (g_c) is T, but micrometeorological measurements of total ET are nevertheless commonly used in this calculation (e.g., Zha et al., 2010; Ji et al., 2011; Kochendorfer et al., 2011). As a strategy to avoid the impact of E on calculations of g_c, some studies have confined the calculations of g_c to times when the canopy is dry (e.g., Sommer et al., 2002; Kosugi et al., 2007) or, more stringently, when soil moisture conditions are dry (e.g., Kume et al., 2011) under the assumption that ET is almost exclusively comprised of T under such conditions. Partitioning results from the present study, however, indicate that E can still account for significant portions of ET under relatively dry conditions (Fig. 2), which can have a large impact on the calculation of g_c (Fig. 4). For instance, E accounts for only 18% of ET on Julian Day 219, yet estimates of g_c are inflated by 86% as a result of this modest contribution. Modeling strategies have been adopted to estimate E and to remove its impact on calculations of g_c. Such an approach was used by Zhang et al. (2006), in which accurate estimates of g_c were needed to apply an isotope-based technique for CO_2 flux partitioning. The partitioning approach described in this study provides an alternative means by which to improve estimates of g_c from micrometeorological-based observations, which can be used to better constrain models of land-atmosphere exchange.

Precipitation events have a transient impact on the ET partitioning, as shown throughout the growing season (Fig. 2) and in detail for dry/wet days (Fig. 5). During relatively wet conditions such as encountered during the period depicted in Fig. 5, ET proceeds at its potential rate. This places a cap on ET, and the enhancement of E following rainfall necessarily means a reduction in T. Although this effect is most prominently observed during the early morning hours when intercepted water is present in the canopy storage and surface soils are at or near saturation (Fig. 5), the enhancement of E at the expense of T appears to linger for several days (Fig. 2).

The enhancement of E (and reduction in T) following rainfall tends to scale with canopy LAI, as shown in Fig. 6. While direct evaporation from canopy interception contributes to this behavior, it probably does not account for the majority of the observed enhancement in E. If overnight rainfall is sufficient (for example, greater than 1 mm or so), the amount held in the interception store would be similar to the maximum storage capacity, $S^c_{\max}$. For corn canopies, this has been approximated by $S^c_{\max} = 0.2\text{LAI}$, with units in mm (Brisson et al., 1998; Kozak et al., 2007). Therefore the amount of E from the interception store would be about 0.5 mm when LAI is at its maximum, whereas the overall enhancement of E is on the order of 1.0–1.5 mm following rainfall for the mature canopy (Fig. 6). Bare soil evaporation likely contributes toward a larger portion of the enhanced E following rainfall events. The enhancement of E from soil evaporation also seems to scale with LAI, simply because bare soil evaporation accounts for a smaller portion of ET before the arrival of rainfall when LAI is higher.

Regardless of the source of E, its enhancement following rainfall events leads to a reduction in T. This could be attributable to the E providing for a moister canopy microclimate, which decreases the humidity gradient across the stomatal openings on the leaf surfaces and has the effect of increasing WUE (i.e., greater carbon gain per unit water loss via transpiration). The concept of transpiration suppression has previously been proposed within the context of irrigation use efficiency (e.g., Tolk et al., 1995) and could be further investigated using partitioned ET flux information generated by the method used in the present study. Ultimately, such information could be used to guide irrigation practices for the purpose of optimizing water use during crop production.

Acknowledgments

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